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THE FORMATION AND MERGER OF COMPACT OBJECTS IN CENTRAL ENGINE OF ACTIVE GALACTIC NUCLEI AND QUASARS: GAMMA-RAY BURST AND GRAVITATIONAL RADIATION

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ABSTRACT

The production rate of compact objects, i.e. neutron stars (NS) and black holes (BH), in active galactic nuclei (AGN) and quasars (QSO), where the frequent supernova explosion is used to explain the high metallicity, is very high due to the interaction between the accretion disk and main sequence stars in the nucleus of the quasar. The compact object-red giant star (RG) binaries can be easily formed due to the large captured cross-section of the red giant stars. The (NS/BH, NS/BH) binary can be formed after the supernova explosion of the (NS/BH, RG) binary. Intense transient gamma-ray emission (gamma-ray burst) and gravitational radiation can result from the merger of these two compact objects. Collision between helium core (Hc) of RG and black hole may also take place and may also result in long duration gamma-ray bursts but no gravitational waves. We estimate that the merger rate of (NS/BH, NS/BH) binaries and (Hc, BH) is proportional to the metal abundance $\left(\frac{\rm NV}{\rm CIV}\right)$ and can be as high as $10^{-3}\left(\frac{\rm NV}{\rm CIV}/0.01\right)$ per year per AGN/QSO.

Subject headings: quasar: emission line – star: neutron star/black hole – gamma-ray: burst – gravitational radiation

1. INTRODUCTION

The basic physical scenario of active galactic nuclei and quasars is generally believed to be a supermassive black hole surrounded by accretion disk which releases the observed huge body of energy (Rees 1984). However in this model one prominent problem is the fuel. Syer, Clark, & Rees (1991) investigate the possibility of accretion disk capturing stars in dense star cluster of nucleus (within 1pc) in order to remove the accretion fuel problem. This interesting interaction has been employed to explain the high metallicity phenomena in active galactic nuclei and quasars by Artymowicz, Lin & Wampler (1993), Zurek et al (1994), especially for broad absorption line (BAL) quasars with extremely high metallicity (sometimes several hundred times that of solar abundance, Shields 1996). It is interesting to note that this process also result in the formation and coalescence of compact objects in the central energy house of active galactic nuclei and quasars which may be sources of frequent γ-ray and gravitational wave bursts.

Gravitational wave could soon be detected directly even emitted from a source located at a cosmological distance because several ground-based gravitational wave experiments including the Laser Interferometer Gravitational-Wave Observatory (LIGO) (Abramovici et al. 1992), VIRGO, TAMA300 and GEO600 are under construction. The best understood of all gravitational-wave sources are coalescing, compact binaries composed of neutron stars and black holes. These NS/NS, NS/BH and BH/BH binaries may give information about the equation of state (EOS) of nuclear matter at high densities (Shibata, Nakamura & Oohara 1992, 1993; Rasio & Shapiro 1994; Zhuge, Centrella & McMillan 1994; Davies et al. 1994; Ruffert, Janka & Schäfer 1996; Cheng & Dai 1998).

In addition the observations of afterglow of Gamma-ray Burst (GRB) lend strong supports to the cosmological origin of GRB (Paczyński 1986, Mao & Paczyński 1992, Meegan et al 1992, Piran 1992) (see a concise review by Greiner 1998 for the afterglow, and Piran 1998). Despite the effort of searching more than 20 years to look for the counterparts of GRB at other wave bands, no known population of objects in the Universe have been identified with any GRB sources (e.g. Fenimore et al. 1993, Fishman & Meegan 1995, Band & Hartmann 1998). Two main reasons to cause this situation. First, the position accuracy of GRB detected by BASTE is so low that a large number of known objects are located in its error box. Secondly, the burst duration is so short that it is very difficult to use other means to reduce the error box. Although the BeppoSAX has observed a dozen of GRBs' afterglows, one of these sources can reduce its error box down to $\sim$ one arc second. But still no confirmed counterparts are identified, even for the well-observed, GBR970228 and GRB970508. On the other hand, the observed isotropic and inhomogeneous distribution of GRBs detected by the BASTE instrument on board the Compton Gamma-Ray Observatory (CGRO) is best explained by a source population at cosmological distances.

Most cosmological GRB models involve compact objects. For examples, (1) neutron star - neutron star/black hole merger (e.g. Paczyński 1986; Eichler et al 1989; Dermer 1992; Narayan, Piran & Shemi 1991; Mao & Paczyński 1992); (2) collision between black hole and Helium core or

white dwarf by Fryer & Woosley (1998), Fryer et al (1998); (3)the phase transition from neutron star to strange star (Cheng & Dai 1996); (4) the transition of normal nuclear matter to matter with pion condensation in neutron star (e.g. Haensel et al 1990, Muto et al 1993); (5) rapidly rotating neutron star with extremely large magnetic field (Usov 1992, Duncan & Thompson 1992); (6) a failed supernova type Ib (Woosley 1993), or microquasar (Paczyński 1998) etc. Therefore, if we want to find the hosts of GRB sources, it is logical to look for cosmological sources with a lot of compact objects. From the stellar evolution point of view, the progenitors of compact objects, e.g. neutron stars, are massive stars (approximately $5 \sim 20 M_\odot$). ¿From the observations of afterglows of GRBs it has been deduced by Paczyński (1998) that GRB may associate with the star formation region. We note that most of the masses of the massive stars, consisting of a lot of heavy elements, will be ejected during the supernova explosion and a metal-rich region will be formed. Naturally, galaxies with high abundance of compact object should be metal-rich. Therefore it is logical to look for cosmological sources with high metal abundance. In order to observe the sources located at cosmological distance, these sources must be luminous. It should be noted that most AGNs/QSOs are metal-rich (Artymowicz, Lin & Wampler 1993, Hamann et al 1997). This may be the real reason why GRBs may be related to AGNs and QSOs as reported by Schartel, Andernach & Greiner (1996), and Burenin et al (1998) who claim there are possible association of γ-ray burst with radio quiet quasar, and with active galactic nuclei, respectively. However the physical scenario of this association remains open if it is true, at least, some of GRB are related with AGNs/QSOs. It has been suggested that GRB may be produced in a star formation region which leads to expectation of the burst rate of GRB proportional to the formation rate of star in the cosmological galaxies (Paczyński 1998). Because the lifetime of AGN/QSO is rather short (generally less than 10^8 yr), the possible host objects of GRB are mostly ones related with galaxies. Alternatively here we suggest that the interaction between accretion disk and stars in dense cluster may lead to the formation of a large number compact objects in the central engine of active galactic nuclei. The formation and interactions among the compact objects in the nuclei might associate with GRB. Therefore active galactic nuclei are one kind of its host objects if GRBs are indeed associated with compact objects.

2. THE MODEL

The mechanism for the enhancement of metal-rich elements has been suggested by a way of evolution of main sequence stars, which are captured by the accretion disk surrounding the supermassive black hole in the center of quasar (for a review cf. Lin & Papaloizou 1996). The captured stars would accrete material from the disk and increase their masses up to 50 solar masses in less than 10^4 years. These massive stars evolve rapidly toward the supernova stage and the ejecta of the supernovae provide enough heavy element to produce the features suggested by observations. The metal abundance expressed in terms of the ratio between NV and CIV is related to the total number of captured main sequence stars $N_{\rm MS}$ during the active phase of quasar as follows (Artymowicz, Lin & Wampler 1993; Zurek et al 1994)

$$\frac{\rm NV}{\rm CIV} \approx 0.01 \left(\frac{N_{\rm MS}}{1.0\times 10^5}\right). \tag{1}$$

However this mechanism results in other implications, such as formation of neutron stars/black holes in the vicinity of the accretion disk. As we will argue in the subsequent section, it exists an efficient way to form compact object - compact object (i.e. NS/BH, NS/BH) binaries via the formation of compact object - red giant star (NS/BH, RG) binaries. The (NS/BH, NS/BH) binary will be formed after the explosion of the red giant star. In such a scheme the merger rate of (NS/BH, NS/BH) binary approximately equals to the capture rate of main sequence star, therefore it is proportional to the metal abundance. If the merger of (NS/BH, NS/BH) binary or Helium core of RG and black hole is one of the possible mechanisms of GRBs, then active galactic nuclei and quasars should associate with GRBs. In fact the coalescence of two compact objects also produces intense transient gravitational waves which should be detected by LIGO/VIRGO in 1Gpc radius.

2.1. *Evolution of the captured stars in the accretion disk*

We assume that the nucleus of the quasar consists of a massive black hole surrounded by an accretion disk, which are enclosed by a star cluster. The structure of disk is described by the standard model in which the local height and the surface density of the accretion disk are given by (e.g. Frank, et al 1992)

$$\left(\frac{h}{R}\right) = 1.6\times 10^{-3}\alpha^{-1/10}\dot{m}^{3/20}M_8^{-1/10}r_{\rm d}^{1/8}, \tag{2}$$

and

$$\Sigma = 1.7\times 10^{7}\alpha^{-4/5}\dot{m}^{7/10}M_8^{1/5}r_{\rm d}^{-3/4}({\rm g\ cm^{-2}}), \tag{3}$$

respectively, and the inward drift velocity due to the outward transportation of the angular momentum in disk reads

$$v_{\rm r} = 4.1\times 10^{4}\alpha^{4/5}\dot{m}^{3/10}M_8^{-1/5}r_{\rm d}^{-1/4}({\rm cm\ s^{-1}}), \tag{4}$$

or the time scale of inward drift is

$$\tau_{\rm r} = 4.0\times 10^{7}\alpha^{-4/5}\dot{m}^{-3/10}M_8^{6/5}\left(\frac{r_{\rm d}}{10^5}\right)^{5/4}({\rm yrs}), \tag{5}$$

where $\dot{m}$ is dimensionless accretion rate scaled with the Eddington limit, α is the viscosity coefficient, $r_{\rm d} = \frac{R}{R_s}$ is the radius of disk normalized by Schwartzchild radius $R_s = \frac{GM_{\rm BH}}{c^2}$, and M_8 denotes the mass of central black hole ($M_{\rm BH}$) in units of $10^8 M_\odot$.

The main sequence stars in the star cluster will be captured by the disk and the number of the captured main sequence stars in the annular $R - R + dR$ is estimated as (Artymowicz, Lin & Wampler 1993),

$$\begin{aligned} dN &= m_* G^2(\Sigma R dR)\frac{32\pi^{1/2}C_d\nu_0\Delta T}{\sigma_0^3} \\ &\approx 0.45\left(\frac{m_*}{M_\odot}\right)\left(\frac{\nu_0}{10^7{\rm pc^{-3}}}\right)\left(\frac{\Delta T}{10^8{\rm yr}}\right)\left(\frac{\sigma_0}{300{\rm kms^{-1}}}\right)^{-3} \\ &\quad \alpha^{-4/5}\dot{m}^{7/10}M_8^{11/5}r_{\rm d}^{1/4}dr_{\rm d} \end{aligned} \tag{6}$$

where ΔT is the active period of quasar, ν_0 is the number density of star cluster at 1 pc in the range of about $10^7/\mathrm{pc}^3$ (Blandford 1991), σ_0 is the dispersion velocity of star in the cluster, and $C_d \approx 6$. Integrating over the disk, there are $\sim 10^5$ main sequence stars captured by disk in the active phase of quasar or the captured rate is $\sim 10^{-3} yr^{-1}$. The captured stars will coorotate with the medium in the disk (Syer et al 1991), and accrete gas from the disk with Bondi rate until a gap appears in disk with condition that the star's Roche radius exceeds the disk scale-height h (Lin & Papaloizou, 1996). The timescale of Bondi accretion is

$$\tau_a = 1.40\times 10^3 \alpha^{2/5} \dot{m}^{-1/10} M_8^{2/5} \left(\frac{r_\mathrm{d}}{10^5}\right)^{3/4} \left(\frac{m}{M_\odot}\right)^{-1} \text{(yrs)}, \tag{7}$$

and the maxium accreted mass of the captured star is limited by

$$\left(\frac{m}{M_\odot}\right) = 17.7 \alpha^{-3/10} \dot{m}^{9/20} M_8^{7/10} \left(\frac{r_\mathrm{d}}{10^5}\right)^{3/8}. \tag{8}$$

This condition is also coincided with that the Bondi radius ($r_\mathrm{B} = Gm_*/c_\mathrm{s}^2$) does not exceed the local height h. With the typical parameters of the quasars and $\alpha = 1$, the maximum accreted mass of the captured stars is in the range of $10 \sim 20\ M_\odot$ (but the maximum mass of the captured stars could be much higher than $20\ M_\odot$ if α is much less than unity). The star in this mass range will evolve off their main sequence quickly and likely become neutron stars plus small fraction of black holes (see e.g. Shapiro & Teukolsky 1983). For more massive stars (m $\geq$ 20 $M_\odot$) they could become neutron stars or black holes (Timmes, Woosley & Weaver 1996). The simple formula of the evolution time scale for the main sequence star is (Meurs & van den Heuvel 1989)

$$\tau_\mathrm{e} = 10^{a_1} \left(\frac{m}{M_\odot}\right)^{a_2}, \tag{9}$$

where the index a_1 and a_2 are tabulated in their table 3. For interested cases, we have $a_1 = 9.3$, $a_2 = -2$ for $3.8 \leq m/M_\odot \leq 12$, and $a_1 = 8.2$, $a_2 = -1$ for star larger than $12 M_\odot$. Substituting parameters for lower mass case into Eq.9, we obtain:

$$\tau_\mathrm{e} = 9.0 \times 10^6 \alpha^{3/10} \dot{m}^{-9/20} M_8^{-7/10} \left(\frac{r_\mathrm{d}}{10^5}\right)^{-3/8} \quad \text{(yrs)}. \tag{10}$$

The higher mass case will evolve faster than that given in Eq.(10). It has been estimated that the main sequence stars start to be captured by the disk at the disk radius $\sim$1 pc (Artymowicz, Lin & Wampler 1993) but the exact value of this radius is not crucial in our model. The more important radius R_c is before which the captured stars finish the evolution of supernova stage. This radius must be larger than that of the tidal radius $R_\mathrm{t} = \left(\frac{M_\mathrm{BH}}{m_*}\right)^{1/3} r_*$, otherwise the captured stars will disrupted by the central massive black hole. This radius can be estimated by equating the radial inward drifting time scale Eq.(5) and the evolution time scale Eq.(11) and is given by

$$r_\mathrm{c} = \frac{R_\mathrm{c}}{R_\mathrm{s}} = 4.0 \times 10^4 \alpha^{44/65} \dot{m}^{-6/65} M_8^{-76/65}. \tag{11}$$

It appears that this radius is always larger than that of R_t for typical quasar parameters.

2.2. *Formation of binaries*

In the early stage, almost all of the captured stars can evolve to neutron stars/black holes with mass m_ns which will be ejected from the disk after supernova explosion. But these neutron stars/black holes can only shoot up to a scale height

$$h_\mathrm{ns} = \frac{v_\infty^2 R_\mathrm{c}^2}{GM_\mathrm{BH}}, \tag{12}$$

where $v_\infty \sim 300$ km/s is the neutron star kick velocity produced by supernova explosion. Taking the typical parameters, $h_\mathrm{ns} \sim 10^{16}$ cm. The compact stars will be oscillating up and down crossing the disk. Artymowicz, Lin & Wampler (1993) also note the possibility of retrapping of compact stars by disk, but the following case is more interesting. Before evolving to compact star, the captured star will go through the red giant phase with radius (R_RG) and mass M_RG. During the close encounter with a neutron star, the red giant star would undergo substantial tidal deformation at the cost of a part of the relative kinetic energy of the orbit. Such a tidal process can eventually dissipate the total positive energy of the initial unbound orbit via oscillations and heating, and a (NS/BH, RG) binary system will be created. One might argue that the velocity dispersion of NS/BH is much larger than the escape velocity of RG at its surface (about 70km/s). However, it is interesting to note the following situation. The surface density of RG $\Sigma_\mathrm{RG} \sim M_\mathrm{RG}/R_\mathrm{RG}^2 \sim 10^7$ g/cm^2 is much larger than that of disk $\sim 10^3$ g/cm^2 at 0.1pc. This leads to an efficient dissipation of NS/BH kinetic energy in the process of encountering RG's envelope. The probability of NS/BH encountering the dense envelope of RG can be easily estimated

$$f = \frac{S_\mathrm{RG}}{S_\mathrm{disk}} \sim 10^{-2}, \tag{13}$$

where S_RG is the total surface area of all RG, and S_disk is the area of disk capturing main sequence star. The drag force acting on NS/BH by the dense envelope of RG reads (Artymowicz et al 1993)

$$F_d = \frac{4\pi G^2 m_\mathrm{ns}^2 \rho C_d}{v_\infty^2}. \tag{14}$$

After N times of encountering the disk, the kinetic energy of NS/BH will be reduced significantly so that NS/BH can be captured by RG through tidal process,

$$\begin{aligned} N &= \frac{v_\infty^4}{8\pi f G^2 m_\mathrm{ns} C_d \Sigma_\mathrm{RG}} \\ &\sim 10^4 \left(\frac{f}{0.01}\right)^{-1} \left(\frac{\Sigma_\mathrm{RG}}{10^7\mathrm{g/cm^2}}\right)^{-1} \left(\frac{v_\infty}{300\mathrm{km/s}}\right)^4, \end{aligned} \tag{15}$$

and the capture time scale of NS/BH by the RG envelope is about

$$\tau_\mathrm{ns,RG} = N \frac{h_\mathrm{ns}}{v_\infty} \sim 10^5 \mathrm{yr}, \tag{16}$$

which is slightly shorter than the life time of RG, therefore a large fraction of RG can be captured by the compact objects in the vicinity of the disk to form (NS/BH, RG) binaries if we take into account the interaction between NS/BH and the envelope of RG. Let us consider the tidal capture rate in more detail. The distance D for the tidal capture to form a (NS/BH, RG) binary can be estimated as (Bhattacharya & van den Heuvel 1991)

$$D \approx 1.75 R_{\rm RG} \left(\frac{m_{\rm ns}}{M_{\rm RG}} \frac{m_{\rm ns}+M_{\rm RG}}{M_\odot} \frac{R_\odot}{R_{\rm RG}} \right)^{\frac{1}{6}} \left(\frac{50{\rm Km/s}}{v_{\rm ns}} \right)^{\frac{1}{3}}, \tag{17}$$

where $v_{\rm ns}$ is the reduced velocity of the compact star. The cross section of this capture process is given by

$$\sigma \approx \pi D^2 \left[1 + \frac{2G(m_{\rm ns}+M_{\rm RG})}{v_{\rm ns}^2} \right], \tag{18}$$

and is $\sim 3\times 10^{28} cm^2$ for typical parameters. The formation rate of (NS/BH, RG) binary thus can be written as

$$\frac{dN_{\rm NR}}{dt} = \left(\frac{N_{\rm ns}}{V_{\rm ns}}\right)\left(\frac{N_{\rm RG}}{V_{\rm RG}}\right) v_{\rm ns}\sigma V_{\rm RG} = k N_{\rm ns} N_{\rm RG}, \tag{19}$$

where $N_{\rm ns}$ and $V_{\rm ns} \sim h_{ns} R_c^2$ ($N_{\rm RG}$ and $V_{\rm RG}$) are the number and occupied volume of compact stars (red giant stars) respectively, and constant $k = v_{\rm ns}\sigma/V_{\rm ns}$. It should be noted that $N_{\rm ns}$ and $N_{\rm RG}$ are time-dependent because the presence of (NS/BH, RG) binary formation results from the tidal interaction between compact stars and red giant stars. The time-dependent numbers of compact stars and red giant stars obey the following equations

$$\frac{dN_{\rm RG}}{dt} = \Gamma - k N_{\rm ns} N_{\rm RG}, \tag{20}$$

$$\frac{dN_{\rm ns}}{dt} = \frac{N_{\rm RG}}{\tau_{\rm RG}} - k N_{\rm ns} N_{\rm RG}, \tag{21}$$

where Γ is the capture rate of main sequence stars by disk, and $\tau_{\rm RG}$ represents the evolution time scale from red giant star to NS/BH (about a few times of 10^5 years). These non-linear equations can be analytically resolved in some interesting stages.

(1) When $t \le \frac{1}{\Gamma}$, the production of red giant stars dominates, we have

$$N_{\rm RG} \approx \Gamma t, \quad \text{and} \quad N_{\rm ns} \approx \left(\frac{\Gamma}{\tau_{\rm RG}}\right) t^2. \tag{22}$$

2) In steady state, the numbers of compact stars and red giant stars reach constants, i.e.

$$N_{\rm RG}(\infty) = \tau_{\rm RG}\Gamma, \quad \text{and} \quad N_{\rm ns}(\infty) = \frac{1}{k\tau_{\rm RG}}. \tag{23}$$

It is clear that the (NS, RG) binary formation rate is a constant, i.e. $\frac{dN_{\rm NR}}{dt} = \Gamma$.

2.3. *Coalescence of (NS/BH, NS/BH) and (BH, Hc) binaries*

The evolution of massive binaries leads to two possibilities: (1) Merging of Helium core of RG and black hole, (2) (NS/BH, NS/BH) binary formations and merging. The first case occurs for very close binaries in which the black hole companion encounters with the Helium core before the secondary evolves into compact object. This process is recently suggested as a GRB mechanism by Fryer & Woosley (1998). The second corresponds to the case which the secondary evolves into compact star faster than that of spiral-in process. Then the (NS/BH, NS/BH) binaries are formed and eventually merge to emit intense transient gamma-rays and graviational waves. The estimations of above processes are given below.

The captured compact star may spiral-in the red giant star with the core mass $M_{\rm core}$ and envelope mass $M_{\rm en}$. Many detail calculations have been done (e.g. Bodenheimer & Taam 1984; Taam & Bodenheimer 1989, Taamr et al 1997). A rough estimation of final separation of the binary after spiral-in can be made by comparing the binding energy of envelope with the difference in total energy of the binary before and after spiral-in (Webbink et al 1983, Verbunt 1993)

$$\frac{D_f}{D_i} = \frac{M_{\rm core}}{M_{\rm RG}} \left(1 + \frac{2D_i}{\alpha_* \lambda R_L} \frac{M_{\rm en}}{m_{\rm ns}} \right)^{-1}, \tag{24}$$

where D_i, and D_f are the initial and final separation respectively, R_L is the Roche radius, which is given by (Eggleton 1983)

$$\frac{R_L}{D_i} = \frac{0.49}{0.6 + q^{-2/3}\ln(1+q^{1/3})}, \tag{25}$$

where q is the mass ratio of (NS/BH, RG) binary system, α_* is the efficiency with wich released binary energy is used to lift the envelope; λ a factor depending on the mass distribution in the envelope of RG. Their product is often taken to be 0.20. The core mass of red giant star for $M_{\rm RG} \ge 7M_\odot$ is given by (Iben 1993),

$$\frac{M_{\rm core}}{M_\odot} = 0.058 \left(\frac{M_{\rm RG}}{M_\odot}\right)^{1.57}. \tag{26}$$

And the radius of core is given by (Paczyński & Kozlowski 1972; Pols & Marinus 1994; Wijers 1998)

$$\frac{R_{\rm core}}{R_\odot} = 0.22 \left(\frac{M_{\rm core}}{M_\odot}\right)^{0.6}. \tag{27}$$

If D_f is smaller than the sum $R_{\rm core} + R_{\rm ns} \approx R_{\rm core}$, after spiral-in the compact star merges with the core of the red giant star. We have calculated some typical cases listed in Table 1. It can be found that the RG massive than $18M_\odot$ will merger with the Helium core before they form a (NS/BH, NS/BH) binary. Even the companion star is a neutron star, it may accrete efficiently material from the red giant to become a black hole during the spiral-in process(Chevalier 1996; Fryer & Woosley 1998). Therefore the merger of (NS/BH, Hc) binary can become γ-ray burst as described by Fryer & Woosley (1998).

There are two possible ways to destroy the formed (NS/RG, RG) binaries: 1) the combining gravitation of central black hole and the dense star cluster, 2) the third encounter from the cluster. It has been shown by Saslaw (1985) that the chance of the later way is rather small.

We can now estimate the action of the first way. If the tidal force from the gravitation of central massive black hole and dense star cluster exceeds the interacting force between the two components, then the (NS/BH, RG) will be disrupted by the tidal force. The tidal force reads

$$F_{\rm tid} = \frac{G(M_{\rm BH}+M_{\rm SC})(m_{\rm c}+M_{\rm RG})}{R^2}\frac{D_i}{R}, \tag{28}$$

where $M_{\rm SC}$ is the mass of dense star cluster, and $m_{\rm c}$ is the mass of the compact object. Then the ratio between the tidal force and the gravitational force (F_B) between the two components is

$$\frac{F_{\rm tid}}{F_{\rm B}} = \frac{M_{\rm BH}+M_{\rm SC}}{M_{\rm RG}}\frac{M_{\rm RG}+m_{\rm c}}{m_{\rm c}}\left(\frac{D_i}{R}\right)^3 \approx 10^{-4}, \tag{29}$$

which means that the formed binaries can survive in its surroundings. On the other hand, consequently the spiral-in process takes place in the binary very fast. The timescale of this process can be roughly estimated under the assumption that the formed (NS/BH, RG) binary keeps the total angular momentum constant. According to Verbunt (1993), this timescale reads

$$\tau_{\rm sp} = \frac{1}{2(1-m_{\rm c}/M_{\rm RG})}\frac{M_{\rm RG}}{\dot{M}} \approx \frac{1}{2}\frac{M_{\rm RG}}{\dot{M}}, \tag{30}$$

where $\dot{M}$ is the rate of mass transfer onto the compact object. For the case of the RG as a donor in (NS/BH, RG) binary system, $\dot{M}$ can be estimated from Bhattacharya & van den Heuvel (1991),

$$\dot{M} = 1.4\times10^{-2}M_1^{2.25}R_1^{0.75}\ (M_\odot\ {\rm yr}^{-1}), \tag{31}$$

where $M_1 = M_{\rm RG}/M_\odot$, and $R_1 = R_{\rm RG}/R_\odot$. We thus obtain

$$\tau_{\rm sp} \approx 35.7M_1^{-1.25}R_1^{-0.75}\ ({\rm yr}). \tag{32}$$

From the above two equations we have the typical timescale for the case of RG with mass $10M_\odot$, $\tau_{\rm sp}\sim 2$ yr. This simply means that the new formed (NS/BH, RG) binary will reach the final stable configuration D_f (listed in the Table 1) within 2 years, and become hard from the soft state very rapidly. It is thus viable to form hard binary in accretion disk. Furthermore, it has been shown in more detail by Magorrian & Tremaine (1999) that the highest tidal disruption rate $10^{-4}{\rm yr}^{-1}$ only take place in faint galaxies ($L < 10^{10}L_\odot$). The tidal disruption of giant star could produce flare as often as every 10^5yr. Therefore it is robust to believe that the present model of star-disk interaction works dominately over tidal capture by supermassive black hole hosting in the center of AGN/QSO in the active phase of AGN/QSO.

The detailed study of orbital changes due to the explosion of supernovae can be found in Pols & Marinus (1994), and Portegies Zwart & Verbunt (1996). On the other hand, Verbunt(1993) argued that this effect can be estimated by assuming that the explosion is instantaneous, and the positions and velocities of the stars are the same after the explosion as before the explosion (Dewey & Cordes 1987). This implies that the distance D_f between the compact star and the core star before the explosion is the periastron distance after the explosion and that the periastron velocity of the new orbit is the same as the orbital velocity in the pre-supernova orbit. Therefore the eccentricity is given by (Verbunt 1993)

$$e_{\rm ns} = \frac{M_{\rm core}-m_{\rm ns}}{2m_{\rm ns}}. \tag{33}$$

The mass center of binary has obtained a speed $v_{\rm cm}$ because of the mass loss and is given by

$$v_{\rm cm} = e_{\rm ns}v_1, \tag{34}$$

where $v_1 = \sqrt{\frac{GM_{\rm core}}{D_f}} \sim 10^8\left(\frac{M_{\rm core}}{4M\odot}\right)^{1/2}\left(\frac{D_f}{1R_\odot}\right)^{1/2}$ cm s^{-1} is the orbital velocity of the exploding component before explosion. This velocity will make the (NS/BH, NS/BH) binary shooting up to a scale height about $\sim 10h_{\rm ns}$. Furthermore, the orbit of the binary is sufficiently small so it should be circularized by tidal interaction and the radius $D_{\rm ns}$ of the circular orbit is given by

$$D_{\rm ns} = (1+e_{\rm ns})D_f. \tag{35}$$

In table I, we list some possible values of $e_{\rm ns}$ and $D_{\rm ns}$ by assuming $m_{\rm ns} = 1.4M_\odot$. We can see that e is larger than unity when $M_{\rm RG}$ is larger than $15M_\odot$. This means that after explosion the binary will be broken. For $m_{\rm ns} = 3M_\odot$, we find that e is always less than unity and D$_f$ is larger than R$_c$ even when $M_{\rm RG}$ equals $20M_\odot$, in other words, there is no merger of massive black hole and helium core.

There are two interesting consequences of the new born (NS/BH, NS/BH) binary. First, the kick velocity will carry the binary to leave the disk up to the distance about $10h_{\rm ns}\sim 10^{17}cm$. Second, since the separation of two compact stars in the (NS/BH, NS/BH) binary is $\sim D_{\rm ns}$, the gravitational radiation of the binary will make these two compact stars merge in the time scale of (Peter 1964)

$$t_{\rm m}(D_{\rm ns},e) = \frac{12}{19}\left(\frac{D_{\rm ns}^4}{\beta c_1^4}\right){\rm Int}(e), \tag{36}$$

with

$$c_1 = \frac{e^{\frac{12}{19}}}{(1-e^2)}\left(1+\frac{121}{304}e^2\right)^{\frac{870}{2299}}, \tag{37}$$

and

$$\beta = \frac{64}{5}\frac{G^3M_1M_2(M_1+M_2)}{c^5}, \tag{38}$$

and Int(e) is the integral (see eq. 5.14 in Peter 1964). Therefore the compact star merger rate should be about Γ. One should not be surprised by the short time scale of merger since t_m is proportional to $D_{\rm ns}^4$ while most of $D_{\rm ns}$ are less than solar radius, and $t_{\rm m}\propto(1-e^2)^{7/2}$ for larger eccentricity.

3. DISCUSSIONS

In this paper we suggest that if the metallicity of the metal-rich quasars result from the capture of the main sequence stars by the accretion disk surrounding the central massive black hole of quasars and the captured stars can increase their masses by accretion so they can evolve off their main sequence branch and move toward the supernova stage which provide the observed metal abundance.

Then the remnant stars are likely compact stars, i.e. neutron stars or black holes. We have shown that the neutron star/black hole density in the vicinity of the disk will be high enough to a population of (NS/BH, RG) bnaries whic can eventually evolve to become either (i) (NS/BH, NS) binaries if the mass of RG is less than $15M_{\odot}$ and merge in a time scale of a few million years or (ii) (NS/BH, Hc) binary.

In a wide range of cosmological GRB models the compact star merger plays an essential role. Since the main sequence star capture rate $\Gamma = 10^{-3}\ \mathrm{yr}^{-1}\left(\frac{\mathrm{NV/CIV}}{0.01}\right)$ is proportional to the metal abundance $\frac{\mathrm{NV}}{\mathrm{CIV}}$ and the compact object binary formation rate equals the main sequence star capture rate in our simple model. Therefore, the GBR burst rate R_{GRB} in AGNs or QSO can be estimated as

$$R_{\mathrm{GRB}} \sim 10^{-3}\eta\frac{\mathrm{NV/CIV}}{0.01}\mathrm{yr}^{-1}\mathrm{QSO}^{-1}, \qquad (39)$$

where η is the beaming factor of the γ-rays which reduces the observed probability of GRBs resulting from the compact star mergers (e.g. η is 0.1-0.01 for NS/NS merger, Ruffert, Janka, Schafer 1996; Ruffert et al. 1997; Ruffert & Janka 1998). Such estimated GRB rate in metal-rich quasars is much high than that of ordinary galaxies, e.g. the merger rate due to the mass exchange and gravitational radiation losses giving a conservative rate $\sim 10^{-6}yr^{-1}$ (Phinney 1991, Narayan et al 1992), or at a higher rate $10^{-(4\sim5)}$ per year (Tutukov & Yungelson 1993, Portegies & Verbunt 1996) in light of the calculations of binary evolution. Of course, the population of AGN/QSO is only 1% of normal galaxies which makes the total burst rate for these two classes of object comparable. However the burst rate for individual AGN/QSO which has exceptional high metal abundant could be very large. It has much higher possibility that the not-yet-identified host of GRB may an AGN/QSO with very high metallicity.

Recently, Dokuchaev, Eroshenko & Ozernoy (1998) propose the possibility of GRBs origin from the evolved galactic nuclei. In their model, GRBs result from the coalescence of the compact object binary which are formed due to the dynamical evolution of cluster and dissipation of gravitational radiation. Carter (1992) proposed that GRBs are produced by the tidal disruption by the central supermassive black hole. Rees (1988) even pointed out that the rate of tidal disruption could be $10^{-4}\mathrm{yr}^{-1}$ which is significantly lower than the capture rate [see eq.(6)] and formation rate of (NS/BH, NS/BH) binaries, particularly the whole star (unless giant star) will be swallowed by the supermassive black hole with mass $> 10^8 M_{\odot}$ since the Roche radius R_t will lie within the horizon radius of the black hole. Therefore it is believed in an ANG/QSO GRB rate due to the presently proposed process may dominate the tidal capture of star by the central black hole. One might argue that there is no AGN/QSO at the locations of GRB970228 and GRB970508 which are detected by BeppoSAX therefore it is unlikely that GRBs are related to this class of object. However, in order to locate the accurate position the BeppoSAX is restricted to long duration GRBs. Popham, Woosley & Fryer (1998) show that only (BH, Hc) merger can produce long duration burst, other mergers [e.g. (NS/BH, NS/BH)] will not produce long duration burst. It is important to note that the lifetime of AGN is typically of 10^8 years, alternatively, the present paper proposed that at least some of GRBs may origin from the active nuclei due to the interaction between the star in cluster and accretion disk, roughly one percent of the observed GRBs. In our model, only very low mass compact star and high mass RG binaries can form (BH, Hc) mergers. For a power law mass function, such binaries will be a very small fraction. It is not too surprised not to identify any AGN/QSO with GRB970228 and GRB970508 which are long duration bursts. Interestingly there are two GRBs with small error box, in which AGN were found. It was reported by Drinkwater et al (1997) that the possible X-ray counterpart of GRB920501 is related with a Seyfert 1 galaxy at $z = 0.315$. Piro et al (1998) report that the first X-ray location of a γ-ray burst by BeppoSAX (within $3'$ radius) contains the quasar 4C 49 with $z = 1.038$. Finally, we want to point out that the basic energy mechanism of gamma-ray bursts in our model are the same as those proposed by other authors, namely GRBs are resulting from the mergers of compact binaries, except the formation rate of the binaries and the location of Gamma-ray bursts. Since our model burst rate is proportional to the metal abundance (cf. eq. 39), we shall predict that if the GRBs can be identified with AGNs/QSOs, these AGNs/QSOs must have high metal abundance.

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Table 1 The calculation of binary formations*

$M_{\rm RG}$	$M_{\rm c}$	$R_{\rm c}$	D_i	D_f	e	$D_{\rm ns}$	$t_{\rm m}$(yr)	Type
10.0	2.155	0.349	296.021	0.621	0.270	0.788	0.804×10^7	(NS, NS/BH)
11.0	2.503	0.381	295.468	0.613	0.394	0.855	0.796×10^7	(NS, NS/BH)
12.0	2.869	0.414	295.003	0.607	0.525	0.925	0.635×10^7	(NS, NS/BH)
13.0	3.253	0.446	294.606	0.601	0.662	0.999	0.359×10^7	(NS, NS/BH)
14.0	3.655	0.479	294.264	0.596	0.805	1.077	0.987×10^6	(NS, NS/BH)
15.0	4.073	0.511	293.966	0.592	0.955	1.158	0.131×10^5	(NS, NS/BH)
16.0	4.507	0.543	293.704	0.589	>1	.....	.....	.....
17.0	4.957	0.575	293.472	0.586	>1	.....	.....	.....
18.0	5.423	0.607	293.265	$0.584< R_{\rm c}$	.....	.....	.....	(Hc, BH)
19.0	5.903	0.638	293.079	$0.582< R_{\rm c}$	.....	.....	.....	(Hc, BH)
20.0	6.398	0.670	292.911	$0.580< R_{\rm c}$	.....	.....	.....	(Hc, BH)

* All parameters are in solar units except e and t_m(yr). The mass of the compact star is taken to be $1.4{\rm M}_\odot$.